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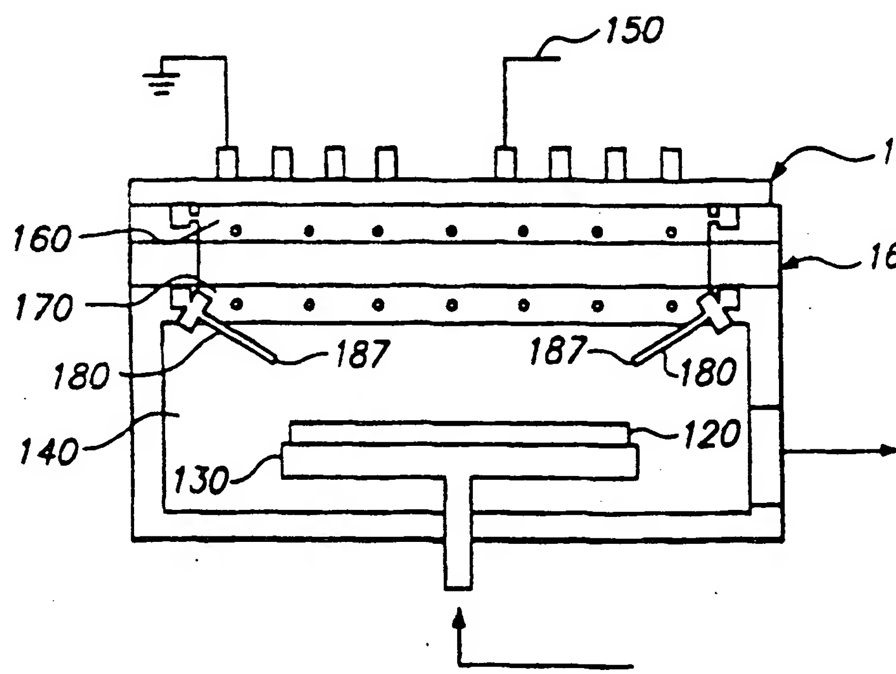
(54) Title: APPARATUS AND METHOD FOR HIGH DENSITY PLASMA CHEMICAL VAPOR DEPOSITION

(57) Abstract



A plasma processing system for processes such as chemical vapor deposition includes a plasma processing chamber (140), a substrate holder (130) for supporting a substrate (120) within the processing chamber, a dielectric member (155) having an interior surface facing the substrate holder, the dielectric member forming a wall of the processing chamber, a gas supply for supplying gas to the chamber, directed towards the substrate, and an RF energy source such as a planar coil (150) which inductively couples RF energy through the dielectric member and into the chamber to energize the process gas into a plasma state. The gas supply may comprise a primary gas ring (170) and a secondary gas ring (160) for supplying gases or gas mixtures into the chamber. The gas supply may further include injectors (180) attached to the primary gas ring which inject gas into the chamber, directed towards the substrate. The plasma processing system may also include a cooling mechanism for cooling the primary gas ring during processing.

APPARATUS AND METHOD FOR HIGH DENSITY PLASMA CHEMICAL VAPOR DEPOSITION

Field of the Invention

The present invention relates to a system and a method for delivering reactants to a substrate in a high density plasma chemical vapor deposition reactor. More particularly, the present invention relates to a system and a method for focusing the delivery of reactants via a gas injection system towards a substrate during processing of the substrate in a high density plasma chemical vapor deposition reactor and thermally controlling the gas injection hardware.

Background of the Invention

Vacuum processing chambers are generally used for chemical vapor depositing (CVD) of materials on substrates by supplying process gas to the vacuum chamber and applying an RF field to the gas. A number of gas distribution systems for integrated circuit processing are known, but the vast majority of known systems are designed for plasma etching or for plasma enhanced CVD (PECVD). Conventional gas distribution systems typically deliver reactants at relatively low flow rates. Showerhead gas injection and diffusive transport systems are commonly used to ensure even distribution over the substrate.

These known systems are not optimized for high density plasma CVD (HDPCVD) processes, such as encapsulation and intermetal dielectric gap filling. In HDPCVD it is important to focus the delivery of reactants such as silane related species onto a substrate, because silane and its radicals, e.g., SiH_3, SiH_2, SiH, and so on, have high sticking coefficients. Directing the silane preferentially onto the substrate is advantageous because it maximizes the substrate deposition rate and minimizes film deposits on various internal surfaces of the reactor.

Efficient silane utilization in HDPCVD requires the reactant gas to be directed onto the substrate from close proximity, with a high flow rate, and even

There is thus a need for a gas distribution system which is optimized for HDPCVD and which provides both an improved deposition rate and an improved deposition uniformity.

Summary of the Invention

It is an object of the present invention to provide gas distribution system for HDPCVD which provides uniform, high flow rate delivery of reactant gases focused preferentially onto the substrate surface, to both maximize deposition rate on the substrate and to minimize the chamber cleaning requirements. It is another object of the present invention to thermally control the gas injection hardware to reduce particle counts within the chamber by minimizing flaking from internal chamber surfaces and by minimizing particle formation caused by thermal pyrolysis within the injection hardware. It is yet another object of the present invention to improve the deposition rate and uniformity of deposition compared to conventional gas distribution systems.

According to one aspect of the invention, a plasma processing system is provided for processing a substrate. The plasma processing system includes a plasma processing chamber, a substrate holder for supporting a substrate within the processing chamber, a dielectric member having an interior surface facing the substrate holder, the dielectric member forming a wall of the processing chamber, a gas supply for supplying process gas (e.g., one or more reactant gases and/or one or more inert gases) into the chamber and towards the substrate, and an RF energy source which inductively couples RF energy through the dielectric member and into the chamber to energize the process gas into a plasma state. The gas supply may include one or more gas rings with or without injectors injecting at least some of the process gas into the processing chamber so as to intersect an exposed surface of the substrate. A cooling mechanism may also be provided to cool the gas supply during processing to minimize film flaking from the gas ring surfaces and prevent excessive heating which could lead to unwanted thermal decomposition of the process gas.

According to another aspect of the present invention, a method is provided for processing a substrate. The method includes placing a substrate on

Detailed Description of the Preferred Embodiments

Figures 2a and 2b illustrate a plasma processing system according to a first embodiment of the present invention. Referring to Figures 2a and 2b, a plasma processing system for processing a substrate 120 comprises a substrate support 130 and a processing chamber 140 enclosing the substrate support. The substrate 120 may be, for example, a semiconductor wafer having diameters such as 4", 6", 8", 12", etc., a glass substrate for making a flat panel display, and so on. The substrate support 130 may comprise, for example, a radio frequency (RF) biased electrode. The substrate support 130 may be supported from a lower endwall of the chamber 140 or may be cantilevered, extending from a sidewall of the chamber 140. The substrate 120 may be clamped to the electrode 130 either mechanically or electrostatically. The processing chamber 140 may, for example, be a vacuum chamber.

A substrate to be processed is inserted into the processing chamber 140. The substrate is processed in the processing chamber by energizing a process gas in the processing chamber into a high density plasma. A source of energy maintains a high density (e.g., 10^{11}-10^{12} ions/cm^3) plasma in the chamber. For example, an antenna 150, such as the planar multiturn coil shown in Figures 2a and 2b, a non-planar multiturn coil, or an antenna having another shape, powered by a suitable RF source and suitable RF impedance matching circuitry inductively couples RF energy into the chamber to provide a high density plasma. However, the plasma can be generated by other sources such as ECR, parallel plate, helicon, helical resonator, etc., type sources. The chamber may include a suitable vacuum pumping apparatus for maintaining the interior of the chamber at a desired pressure (e.g., below 5 Torr, preferably 1-100 mTorr). A dielectric window, such as the planar dielectric window 155 of uniform thickness shown in Figures 2a and 2b or a non-planar dielectric window, is provided between the antenna 150 and the interior of the processing chamber 140 and forms the vacuum wall at the top of the processing chamber 140.

A gas supply supplying process gas into the chamber includes a primary gas ring 170 below the dielectric window 155. The gas ring 170 may be

ensure that any potential particle flakes from the injectors will not fall onto the substrate and contaminate it. The injectors may all be the same length or alternatively a combination of different lengths can be used to enhance the deposition rate and uniformity. The injectors are oriented such that at least some of the injectors direct the process gas in a direction which intersects the exposed surface of the substrate.

As opposed to previous gas injection systems designs which rely predominantly on diffusion to distribute process gas above the substrate, the injectors according to one embodiment of the present invention are oriented to inject process gas in a direction which intersects an exposed surface of the substrate at an acute angle. The angle or axis of injection may range from about 15 to < 90 degrees, preferably 15 to 45 degrees from the horizontal plane of the substrate. The angle or axis of injection may be along the axis of the injector or, alternatively, at an angle of up to 90 degrees with respect to the axis of the injector, as shown in Figure 11. The exit orifice diameter of the injectors may be between 0.010 and 0.060 inches, preferably about 0.020 to 0.040 inches. The hollow core of the injectors 180 may be drilled to about twice the diameter of the exit orifices 187 to ensure that sonic flow occurs at the exit orifice and not within the core of the injector. The flow rate of SiH_4 is preferably between 25-300 sccm for a 200 mm substrate but could be higher for larger substrates.

Due to the small orifice size and number of injectors and large flowrates of SiH_4, a large pressure differential develops between the gas ring 170 and the chamber interior. For example, with the gas ring at a pressure of >1 Torr, and the chamber interior at a pressure of about 10 mTorr, the pressure differential is about 100:1. This results in choked, sonic flow at the orifices of the injectors. The interior orifice of the injector may also be contoured to provide supersonic flow at the outlet.

Injecting the SiH_4 at sonic velocity inhibits the plasma from penetrating the injectors. This design prevents plasma-induced decomposition of the SiH_4 and the subsequent formation of amorphous silicon residues within the gas ring and injector extension tubes.

187 is a few centimeters or more above the substrate 120, the radial location of the injector orifices has a much larger impact on the deposition rate than does the vertical location.)

In case 1, the overall deposition rate is higher, that is 10800 Angstroms/minute compared to 9200 Angstroms/minute for case 2. This is because in case 1, the silicon containing process gas is more concentrated over the center of the substrate. However, this increased deposition rate for case 1 comes at the expense of a decreased uniformity, which is 8.1% (1σ) for case 1 compared to 4.1 % for case 2. By concentrating more of the silicon containing process gas onto and above the center of the substrate, the deposition rate on the outer (radial) region of the substrate is not increased in the same proportion as the deposition rate in the center. On the other hand, by positioning the injector orifices 187 further outward, the overall deposition rate is reduced, but the uniformity is improved. Hence, for a constant angle of injection (in this case 22.5 degrees) with respect to the substrate, there is a trade-off between deposition rate and uniformity, which occurs as the radial position of the injection point is varied.

The direction of injection from the gas ring 170 can, however, be optimized for each injector, so as to preferentially direct the process gas onto specific regions of the substrate. For example, in optimizing gas ring 170 for case 1, the angle of injection could be adjusted to preferentially direct more silicon-containing gas onto the substrate surface just inside of the substrate periphery. This would lead to an increase in the local deposition rate on the substrate and thereby improve the uniformity.

Figure 3b shows experimental data which illustrate the capability for optimizing the deposition rate and uniformity of the plasma processing system according to the present invention by selecting the appropriate angle of injection for a given injection location. Both cases illustrated in Figure 3b were obtained at the same conditions (plasma source power = 2500 Watts, electrode bias power = 2000 W, SiH_4 flow = 250 sccm, O_2 flow = 350 sccm, pressure = 14 mTorr) with identical injection locations (16 injectors, equally spaced

flux distribution over the substrate, with a relatively small number of injectors. According to the present invention, however, the density of the jet and the chamber ambient are so low that the jet rapidly transitions to the free molecular flow regime.

In the free molecular flow regime, the jet is so rarefied that a shock structure cannot be established, and the jet simply expands as a Prandtl-Meyer expansion, with an effectively frozen (constant) temperature and velocity. Figure 2 illustrates exemplary flow streamlines of the gas jet from an injector. Referring to Figure 2, in the expansion, the flow streamlines appear to radiate from a point source. The density decreases along each streamline in proportion to the inverse square of the distance from the source, and the variation of density from streamline to streamline (with polar angle Θ) is approximately independent of the polar coordinate R. Thus, for example, at an exemplary flow rate of 200 sccm SiH_4 from 16 injectors having 0.020 inch diameter orifices, a chamber pressure of 10 mTorr and a gas ring pressure of 3.9 Torr, the total included angle of the conical expansion is approximately 150 degrees. This expansion is less divergent and thus more collimated than the cosine distribution associated with a purely effusive flow.

The centerline density decreases as the square of the distance from the jet exit. That is, the local gas density ρ is given as:

(1) $$\rho(R,\Theta = 0) \propto (\rho(R=0,\Theta=0)) / R^2$$

where R and Θ are polar coordinates centered at the jet exit, with $\Theta = 0$ defined as the jet axis. In addition, the density for such as expansion decreases with a $\cos^2\Theta$ dependence, that is:

(2) $$\rho(R,\Theta) = \rho(R,0)\cos^2(\pi\Theta/2\phi)$$

where ϕ is an empirical constant which depends upon the specific heat ratio for the injected gas. For example, $\phi = 1.66$ for nitrogen. By combining equation 1 and equation 2 and realizing that the velocity is constant beyond a few jet diameters, the flux J is determined as a function of position within the expansion as:

(3) $$J_{SiH4}(R,\Theta) = \text{constant} \cdot \rho(R,\Theta)$$

The water cooling of the gas ring 170 may be accomplished by using two independent welded tubes 185 as shown in Figure 6 or by using a dual tube structure. Alternatively, a water cooling tube (not shown) may be spirally wrapped around the gas ring 170. The water cooling provides thermal control to minimize flaking from the gas ring and also prevents excessive heating of the gas ring due to high density plasma exposure.

Additionally, radiative cooling may be used to limit the chamber wall and gas ring temperatures and prevent thermal decomposition.

Figure 7 illustrates a plasma processing system according to a third embodiment of the present invention. Referring to Figure 7, the plasma processing system may include a cantilevered water-cooled gas ring 170 and injectors 180. The gas ring 170 may also be supported from the chamber floor.

According to this embodiment, reactant gases may be injected toward the substrate in the same manner as described above with regard to the first embodiment. Radiative cooling may be used to limit the chamber wall and gas ring temperatures. Additionally, the lower gas ring may be water-cooled as described above with regard to the second embodiment. Thus, the third embodiment provides uniform, directed deposition onto a substrate as well as thermal control of the gas injection hardware to minimize flaking.

Figures 8a-8d illustrate detailed views of exemplary injectors in a plasma processing system according to the present invention. For simplicity of illustration, some elements of the plasma processing system, such as the antenna 150 and the gas rings 160 and 170, are not shown. Figures 8a and 8c depict examples of orientations of the injector 180 with respect to the substrate 120. Figure 8a shows the injector 180 oriented approximately 45 degrees from the horizontal plane of the substrate 120. Figure 8c shows an alternative but less optimal orientation of the injector 180 at 90 degrees from the horizontal plane of the substrate 120. Although not shown, preferably the axis of injection (i.e., gas flow direction) is 15 to 45 degrees from the horizontal plane of the substrate 120.

semiconductor applications which are predominately chemical etching systems, such as chlorine etching of aluminum.

The foregoing has described the principles, preferred embodiments and modes of operation of the present invention. However, the invention should not be construed as being limited to the particular embodiments discussed. Thus, the above-described embodiments should be regarded as illustrative rather than restrictive, and it should be appreciated that variations may be made in those embodiments by workers skilled in the art without departing from the scope of the present invention as defined by the following claims.

6. The system of Claim 5, wherein said gas supply further comprises a secondary gas ring supplying an additional gas or gas mixture into said chamber.

7. The system of Claim 5, wherein said gas supply further comprises injectors connected to said primary gas ring, the injectors injecting said gas or gas mixture into said chamber such that at least some of the gas or gas mixture is directed toward said substrate.

8. The system of Claim 7, wherein the injectors are located near or outside of the substrate periphery.

9. The system of Claim 7, wherein said injectors inject said gas or gas mixture into said chamber at an angle over 15 degrees with respect to the exposed surface of said substrate and/or the injectors form the gas or gas mixture into a plurality of gas flows which overlap each other in an area above the substrate.

10. The system of Claim 5, wherein said primary gas ring is cantilevered.

11. The system of Claim 5, further comprising a cooling mechanism cooling said primary gas ring during processing.

12. The system of Claim 11, wherein the cooling mechanism comprises means for supplying an electrically non-conductive cooling liquid to prevent excessive heating during processing of the substrate.

13. The system of Claim 7, wherein the injectors inject at least some of the gas or gas mixture at a sonic or supersonic velocity.

19. The method of Claim 17, wherein injectors are connected to said primary gas ring, the injectors injecting at least some of said gas or gas mixture into said chamber and directed toward said substrate

20. The method of Claim 19, wherein the injectors are located near or outside of the substrate periphery.

21. The method of Claim 19, wherein said injectors inject at least some of said gas or gas mixture into said chamber at an angle over 15 degrees with respect to the exposed surface of said substrate.

22. The method of Claim 16, wherein the process gas is energized by an RF antenna in the form of a planar coil.

23. The method of Claim 16, wherein the process gas is energized by an RF antenna in the form of a non-planar coil.

24. The method of Claim 17, wherein said primary gas ring is cantilevered, and the method further comprises a step of cooling the primary gas ring during processing.

25. The method of Claim 24, wherein said step of cooling comprises passing an electrically non-conductive cooling liquid in heat transfer contact with the primary gas ring to prevent excessive heating of the primary gas ring during processing of the substrate.

26. The method of Claim 22, wherein the layer of material deposited on the substrate comprises a silicon-containing layer.

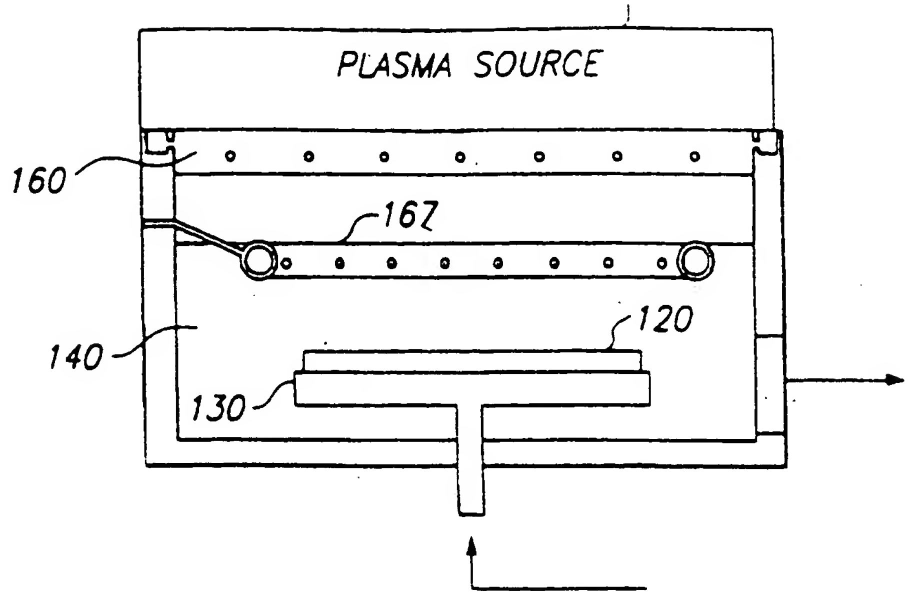

110
PLASMA SOURCE
160
167
140
120
130

FIG. 1

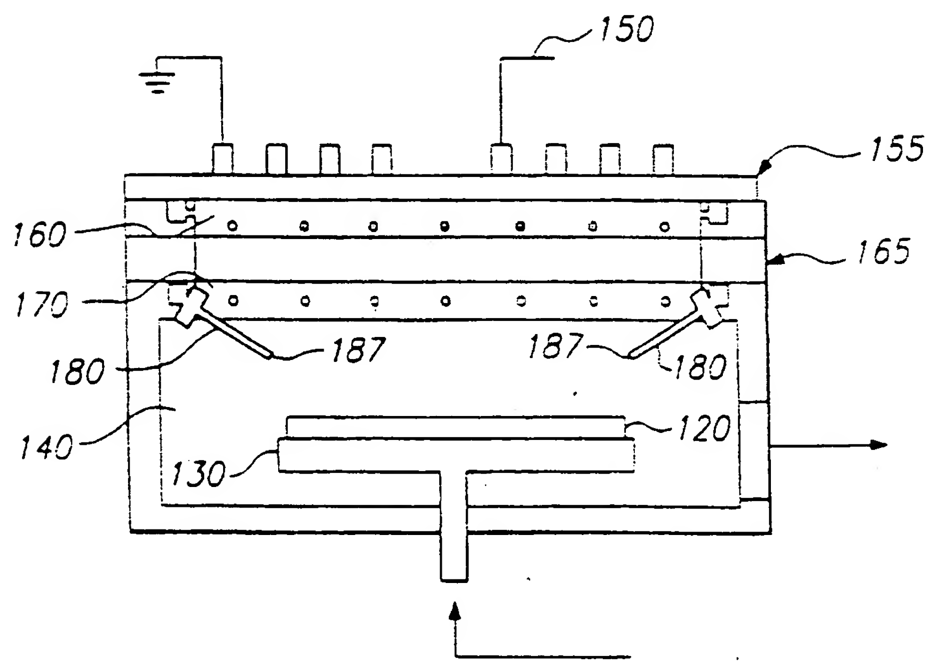

150
155
160
165
170
180
187
187
180
140
120
130

FIG. 2a

COMPARISON OF RATE FOR DIFFERENT INJECTOR LOCATIONS

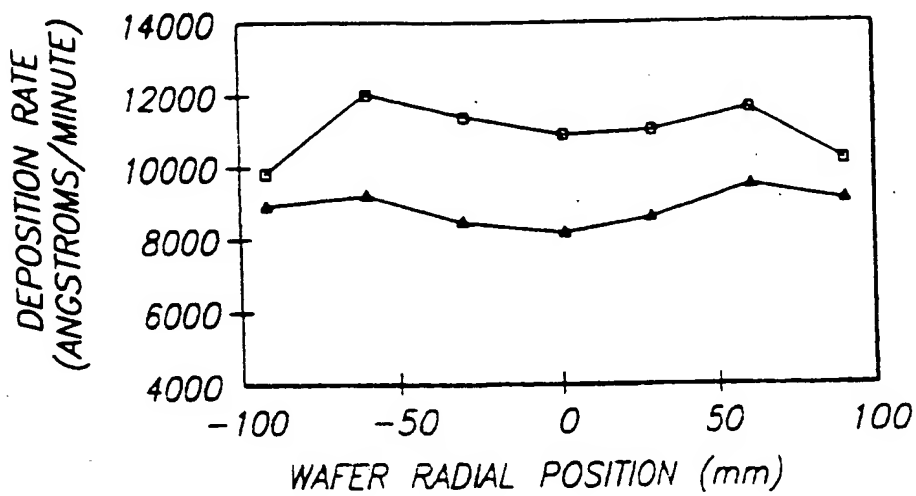


FIG. 3a

GAS INJECTION COMPARISON (0 DEG VS 30 DEG DOWN)

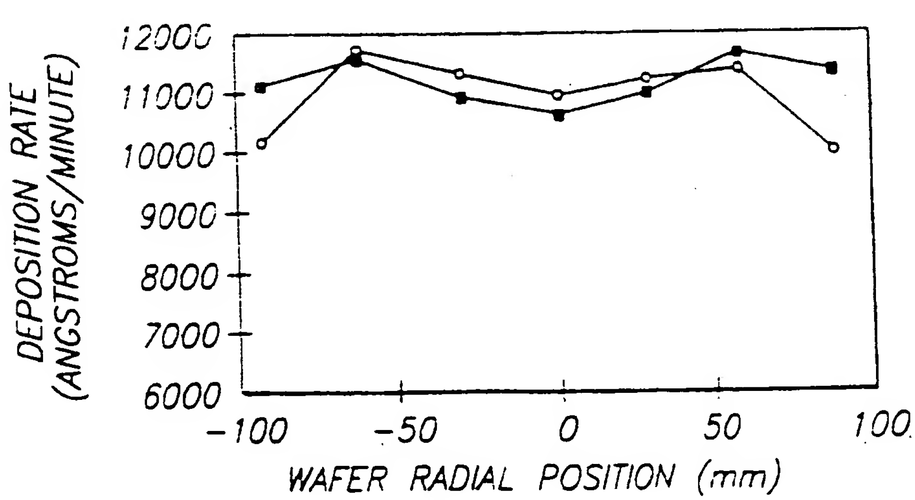


FIG. 3b

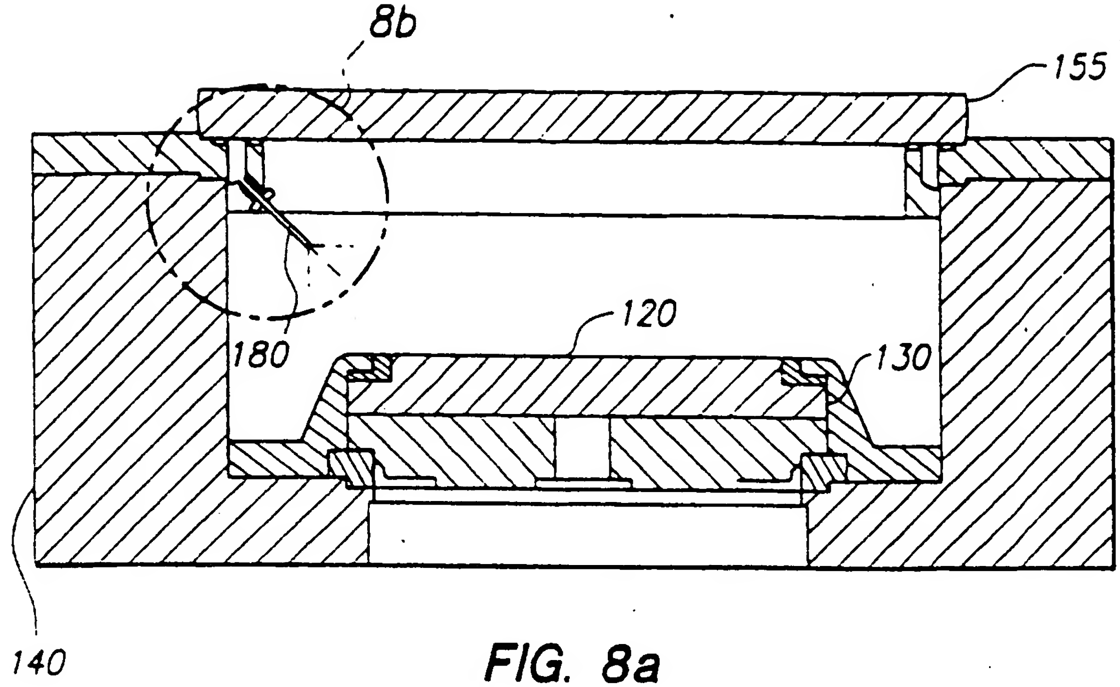


FIG. 8a

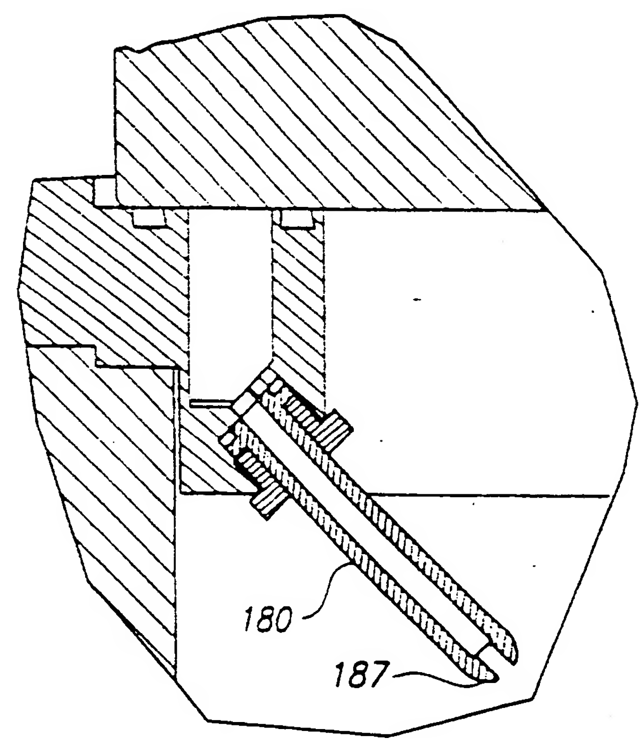


FIG. 8b

7/8

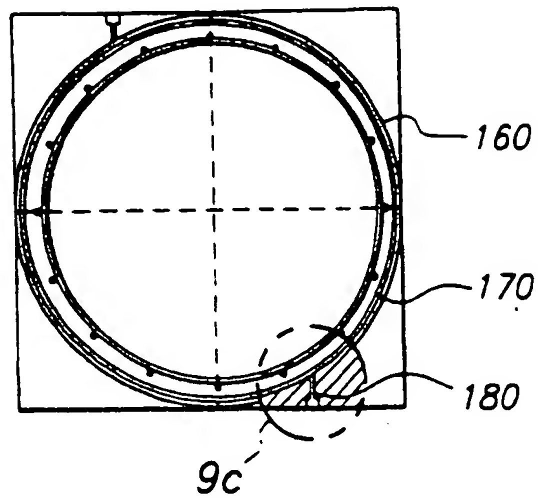


FIG. 9a

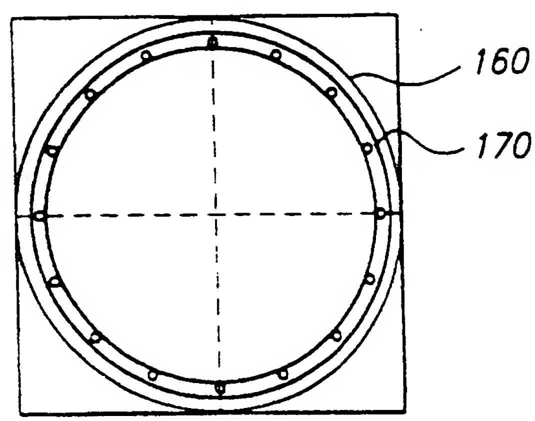


FIG. 9b

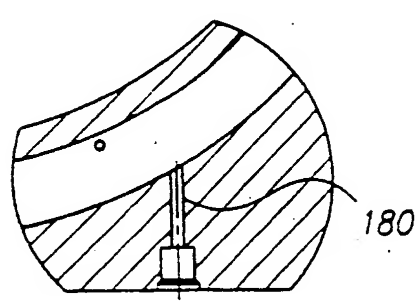


FIG. 9c

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 C23C16/50 H01J37/32 C23C16/44

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 C23C H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 522 934 A (SUZUKI AKIRA ET AL) 4 June 1996 see column 10, line 58 - column 11, line 20; figures 12,13	1-3,16, 17
X	EP 0 709 875 A (APPLIED MATERIALS INC) 1 May 1996 see column 4, line 41 - column 5, line 19; figures 1,2	1-3,16, 17
A	EP 0 520 519 A (APPLIED MATERIALS INC) 30 December 1992 see page 17, line 41 - page 18, line 11	11,12, 24,25
A	EP 0 641 013 A (APPLIED MATERIALS INC) 1 March 1995 see column 8, line 8 - column 10, line 24; claims 1,14,15; figure 6	13

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 September 1997	30.09.97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Patterson, A